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# ATTENUATION OF FRAGMENT VELOCITIES DUE TO THE DEFORMATION RESISTANCE OF THE CASING

TECHNICAL REPORT

by

GORDON A. BRUGGEMAN

OCTOBER 1966

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**ATTENUATION OF FRAGMENT VELOCITIES DUE TO THE  
DEFORMATION RESISTANCE OF THE CASING**

**Technical Report AMRA TR 66-33**

**by**

**Gordon A. Bruggeman**

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ATTENUATION OF FRAGMENT VELOCITIES DUE TO THE DEFORMATION RESISTANCE  
OF THE CASING

ABSTRACT

Estimates are made of the energy required to expand an exploding shell casing relative to the kinetic energies of the fragments. It is shown that the energy of deformation detracts very little from the ultimate fragment velocities.

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## ATTENUATION OF FRAGMENT VELOCITIES DUE TO THE DEFORMATION RESISTANCE OF THE CASING

In predicting the velocity of fragments produced by an exploding shell, neither Gurney<sup>1</sup> nor Thomas<sup>2</sup> take into consideration the energy required to expand the metal casing against the resulting tensile stresses which produce the plastic flow. Observations that the fragment velocities obtained with relatively brittle materials, such as cast iron, are essentially the same as those obtained with ductile casing materials would indicate that this energy is small compared with the kinetic energies imparted to the fragments and the explosion products.

The following approach to an analytical evaluation of the restraining effect is by no means rigorous. The model it employs is that of a gas, initially at a very high pressure, expanding uniformly within the confines of a thin-walled cylindrical casing of infinite length. It does not consider any of the details of the detonation process. Although the model is not exact, it may provide a basis for evaluating the orders of magnitude of the various factors contributing to the final fragment velocities.

Consider first the conditions of velocity and pressure existing within the explosive gases. At any time  $t$  the velocity of the gases may be assumed to vary linearly from zero along the axis of the casing ( $r=0$ ) to the value  $v_R$  adjacent to the casing ( $r=R$ ), as given by

$$v = \frac{r}{R} v_R. \quad (1)$$

Since both  $v_R$  and  $R$  depend upon  $t$ , the gas velocity will depend upon both  $r$  and  $t$ .

In order for the gases to accelerate as they expand, a pressure gradient must exist which results in a net force acting radially outward on each element of gas volume, as illustrated in Figure 1. Equating this net force to the mass per unit length of the element times its radial acceleration results in

$$[p(r,t) - p(r + dr,t)] r d\theta = \left( \frac{\rho_c \pi R_0^2}{\pi R^2} \right) r dr d\theta \frac{d^2 r}{dt^2} \quad (2)$$

where  $p(r,t)$  = pressure at radius  $r$  at time  $t$ ,

$\rho_c$  = initial mass density of the explosive,

$R_0$  = initial radius of the casing.

<sup>1</sup>GURNEY, R. W. *The Initial Velocities of Fragments from Bombs, Shell, and Grenades*. U. S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Report No. 405, September 1943.

<sup>2</sup>THOMAS, L. H. U. S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Report No. 475.

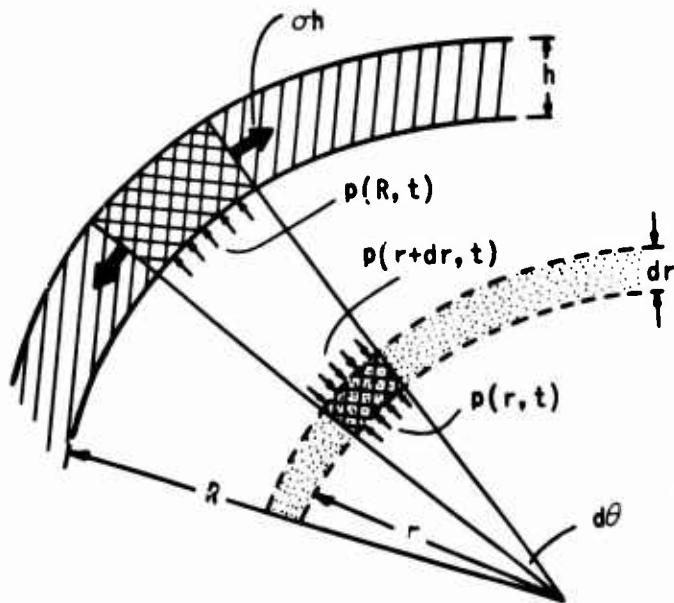


Figure 1. FORCES ACTING WITHIN AN EXPLODING SHELL

Since

$$p(r + dr, t) = p(r, t) + \frac{\partial p}{\partial r} dr, \quad (3)$$

Equation 2 becomes

$$-\frac{\partial p}{\partial r} = \frac{\rho_c R_o^2}{R^2} \frac{d^2 r}{dt^2}. \quad (4)$$

This may be rewritten

$$-\frac{\partial p}{\partial r} = \rho_c \left( \frac{R_o}{R} \right)^2 \frac{dv}{dt} \quad (5)$$

$$\text{or} \quad -\frac{\partial p}{\partial r} = \rho_c \left( \frac{R_o}{R} \right)^2 \left( \frac{\partial v}{\partial r} \frac{dr}{dt} + \frac{\partial v}{\partial R} \frac{dR}{dt} \right). \quad (6)$$

From Equation 1

$$\frac{\partial v}{\partial r} = \frac{v_R}{R} \quad (7a)$$

and

$$\frac{\partial v}{\partial R} = \frac{r}{R} \frac{dv_R}{dR} - \frac{r}{R^2} v_R. \quad (7b)$$

Substituting in Equation 6,

$$-\frac{\partial p}{\partial r} = \rho_c R_o^2 \frac{v_R}{R^3} \frac{dv_R}{dR} r \quad (8a)$$

or

$$-\frac{\partial p}{\partial r} = 2 f(R) r, \quad (8b)$$

where  $f(R)$  is defined by

$$f(R) \equiv \rho_c \frac{R_o^2}{2} \frac{v_R}{R^3} \frac{dv_R}{dR}. \quad (9)$$

Equation 8b can be integrated to give

$$p(r, t) = p(o, t) - f(R) r^2. \quad (10)$$

In order to evaluate the term  $p(o, t)$ , the equation of state for the adiabatically expanding gases is taken to be

$$p_{av} V^\gamma = p_o V_o^\gamma \quad (11a)$$

or

$$p_{av} R^{2\gamma} = p_o R_o^{2\gamma}, \quad (11b)$$

where  $V$  = instantaneous gas volume,

$V_o$  = initial gas volume,

$p_o$  = pressure the instant after detonation,

$p_{av}$  = an average pressure within the casing, which is taken to be the average of  $p(o,t)$  and  $p(R,t)$  or, from Equation 10

$$p_{av} = p(o,t) - 1/2 f(R) R^2. \quad (12)$$

Combining Equations 11 and 12 and substituting for  $p(o,t)$  in Equation 10

$$p(r,t) = p_o \left( \frac{R_o}{R} \right)^{2\gamma} - \frac{1}{2} f(R) r^2. \quad (13)$$

Hence, the pressure acting against the casing is

$$p(R,t) = p_o \left( \frac{R_o}{R} \right)^{2\gamma} - \frac{1}{2} f(R) R^2. \quad (14)$$

The internal pressure given by Equation 14 produces a tensile stress in the cylindrical casing which opposes the expansive effect of the pressure. The forces acting per unit length on an element of the casing are shown in Figure 1, where  $\sigma$  is the tensile stress resisting the influence of the internal pressure. The sum of the radial components of these forces may be set equal to the mass of the casing element times its radial acceleration. Thus,

$$p(R,t)Rd\theta - \sigma h d\theta = \rho_M h R d\theta \frac{d^2 R}{dt^2} \quad (15)$$

where  $h$  = instantaneous thickness of the casing,

$\rho_M$  = mass density of the casing material.

Conservation of volume requires that

$$h = \left( R_o / R \right) h_o, \quad (16)$$

where  $h_o$  is the initial thickness of the casing. Substituting for  $p(R,t)$  from (14), Equation 15 may be written



$$p_o R_o^{2\gamma} R^{-(2\gamma - 1)} - \frac{1}{4} \rho_c R_o^2 v_R \frac{dv_R}{dR} - \sigma h_o \frac{R_o}{R} = \rho_M h_o R_o v_R \frac{dv_R}{dR}. \quad (17)$$

Johnson et al<sup>3</sup> have studied the stress-strain relationship for several metals during high deformation rates and report basically two types of behavior: (1) the stress-strain curve is similar to that found in a conventional or static tensile test but with a rate of work hardening roughly twice the static value; and (2) the stress jumps immediately to a high value in excess of the static tensile strength and remains constant thereafter, independent of the strain. For the first case a relationship of the form

$$\sigma = \sigma_o \epsilon^n \quad (18)$$

may be assumed where

$$\epsilon = \ln \frac{R}{R_o} \quad (19)$$

and  $\sigma_o$  and  $n$  may be taken to be twice their static values. The second case would be described by

$$\sigma = U \quad (20)$$

where  $U$  may be estimated as three times the conventional ultimate tensile strength. Normally  $n$  is expected to decrease with increasing strain rate, contrary to the above report. However, the behavior described by Johnson et al will be considered since it represents a more extreme situation and will yield a conservatively high estimate of the deformation energy.

For the first case (17) becomes

$$p_o R_o^{2\gamma} R^{-(2\gamma - 1)} - \frac{1}{4} \rho_c R_o^2 v_R \frac{dv_R}{dR} - \sigma_o \left( \ln \frac{R}{R_o} \right)^n h_o \frac{R_o}{R} = \rho_M h_o R_o v_R \frac{dv_R}{dR}, \quad (21)$$

which may be integrated directly to give

$$\frac{p_o R_o}{2(\gamma - 1)} \left[ 1 - e^{-2\epsilon(\gamma - 1)} \right] - \frac{\sigma_o h_o}{n + 1} \epsilon^{n+1} = \frac{1}{2} \left( \rho_M h_o + \frac{1}{4} \rho_c R_o \right) v_R^2. \quad (22)$$

Similarly the second case becomes, after integration,

$$\frac{p_o R_o}{2(\gamma - 1)} \left[ 1 - e^{-2\epsilon(\gamma - 1)} \right] - U h_o \epsilon = \frac{1}{2} \left( \rho_M h_o + \frac{1}{4} \rho_c R_o \right) v_R^2. \quad (23)$$

Multiplying by  $2\pi R_o$  both Equations 22 and 23 can be put in the form

<sup>3</sup>JOHNSON, R. C., STEIN, B. A., and DAVIES, R. S. *Basic Parameters of Metal Behavior Under High Rate Forming*. Arthur D. Little, Inc., Contract DA-19-020-ORD-5239, Fifth Interim Report to U. S. Army Materials Research Agency, WAL TR 111.2/20-4, April 1962 - June 1962.

$$\frac{1}{2} \left( M + \frac{1}{2} C \right) v_R^2 = \left\{ \frac{P_0}{\rho_c (\gamma - 1)} \left[ 1 - e^{-2\epsilon(\gamma - 1)} \right] - \frac{2\sigma'}{\rho_c} \frac{h_0}{R_0} \epsilon \right\} C, \quad (24)$$

where  $M$  = the mass of the casing,

$C$  = the mass of the explosive,

$$\sigma' = \frac{\sigma_0 \epsilon^n}{n + 1} \quad \text{for } \sigma = \sigma_0 \epsilon^n$$

$$\sigma' = U \quad \text{for } \sigma = U.$$

Gurney's formula is identical in form:

$$\frac{1}{2} \left( M + \frac{1}{2} C \right) v^2 = EC, \quad (25)$$

where  $v$  is the ultimate velocity of the casing and  $E$  is the energy per unit mass of explosive ultimately converted to the kinetic energies of the casing and the explosive gases. Equation 24 may be rewritten

$$\frac{1}{2} \left( M + \frac{1}{2} C \right) v_R^2 = EC, \quad (26)$$

where  $E$  is the energy per unit mass of explosive which has actually been converted to kinetic energy as a function of time. Thus,

$$E = \frac{P_0}{\rho_c (\gamma - 1)} \left[ 1 - e^{-2\epsilon(\gamma - 1)} \right] - \frac{2\sigma'}{\rho_c} \frac{h_0}{R_0} \epsilon, \quad (27)$$

and for long times

$$E = E. \quad (28)$$

The first term in Equation 27 is the contribution of the internal gas pressure to the kinetic energies of the casing and explosive gases. It increases with strain (and hence time) and approaches a final limiting value at large values of the strain. At a strain of 0.7 the casing and gases should have achieved over 90 percent of their final kinetic energies. This is exactly the strain (or time) dependence predicted by Thomas (Ref. 2, Equation 5.7). In reality, however, a final limiting value is probably reached at an earlier stage than anticipated from (27) since, when the casing fractures (or shortly thereafter), the effectiveness of the expanding gases will be reduced due to the gases escaping around the fragments. Hence the kinetic energy actually derived from the internal gas pressure will be less than that computed from (27).

The second term in (27) is a negative contribution to the kinetic energy arising from the resistance of the casing to plastic flow. As would be expected this term is larger for small-diameter, thick-walled casings, i.e., larger values of  $h_0/R_0$ . Furthermore, since

$$\frac{h_0}{R_0} = 2 \frac{\rho_M / \rho_c}{C/M}, \quad (29)$$

the resistance to plastic flow has a greater effect when the charge:mass ratio is low. The term increases continuously as the strain increases, implying that if the casing were capable of expanding indefinitely without breaking, its kinetic energy would eventually revert entirely to energy of deformation and the expansion of the casing would cease. In reality, however, even ductile casing materials will fracture before the radius has expanded to 1-1/2 times its initial size (corresponding to a strain of about 0.4).

The extent to which the resistance of the casing to plastic flow detracts from the energy available from the expanding gases may be seen in Table I for both types of stress-strain behavior. Here are tabulated, for various values of the strain  $\epsilon$ , the two terms appearing in Equation 27 computed for three different size casings and two values of the initial gas pressure. The casing material is taken to be AISI 1060 steel, quenched and tempered at 1200 F, for which the following constants apply:

$$\sigma_0 = 3.7 \times 10^5 \text{ psi}^*$$

$$n = 0.3^*$$

$$U = 400,000 \text{ psi}^\dagger$$

$$\rho_M = 0.28 \text{ lb/cu in.}$$

Table I. CONTRIBUTIONS TO THE KINETIC ENERGY OF AN EXPLODING CASING

$\epsilon$	Energy Contribution from Internal Pressure (in-lb) $P_0$ (psi)		Negative Energy Contribution from Resistance to Plastic Flow (in-lb)					
			$\sigma = \sigma_0 \epsilon^n$ $R_0/h_0$			$\sigma = U$ $R_0/h_0$		
	$3 \times 10^6$	$2 \times 10^6$	10	5	3	10	5	3
0.01	$3.7 \times 10^8$	$2.5 \times 10^8$	$0.01 \times 10^8$	$0.02 \times 10^8$	$0.03 \times 10^8$	$0.01 \times 10^8$	$0.03 \times 10^8$	$0.04 \times 10^8$
0.05	17.6	10.7	0.08	0.15	0.25	0.07	0.13	0.20
0.1	32.3	21.6	0.18	0.36	0.60	0.13	0.26	0.39
0.2	55.0	36.6	0.45	0.89	1.49	0.26	0.53	0.79
0.3	71.0	47.4	0.76	1.51	2.52	0.39	0.79	1.18
0.04	82.3	54.8	1.10	2.20	3.67	0.53	1.05	1.58
Fracture	—	—	—	—	—	—	—	—
0.5	(90.2)	(60.2)	1.10	2.20	3.67	0.53	1.05	1.58
0.6	(95.8)	(63.8)	1.10	2.20	3.67	0.53	1.05	1.58
0.7	(99.7)	(66.4)	1.10	2.20	3.67	0.53	1.05	1.58
$\infty$	(109.)	(72.6)	1.10	2.20	3.67	0.53	1.05	1.58

\*Two times static test values.

†Three times static test value.

The explosive was considered to be Composition B, for which the following constants were assumed:

$$\rho_c = 0.061 \text{ lb/cu in}$$

$$\gamma = 2.75$$

$$p_0 = 3 \times 10^6 \text{ psi (Case 1)}$$

$$p_0 = 2 \times 10^6 \text{ psi (Case 2).}$$

It must be realized that the negative contribution to the kinetic energy due to the resistance to plastic flow can get no larger than those values which correspond to the strain at the time of fracture. Hence, the maximum energy absorbed would be that associated with the maximum attainable strain, i.e.,  $\epsilon = 0.4$ . Table I is representative of casings exhibiting this ductile-type behavior. Brittle casings would fracture at a much lower value of strain and would therefore absorb considerably less energy than ductile casings. Thus, from Table I, a brittle casing which might fracture at a strain of 0.1 would absorb less than 25 percent of the energy a ductile casing would absorb.

Even for the most unfavorable conditions, namely a thick-walled ductile casing ( $R_0/h_0 = 3$ ); the lowest initial pressure considered to be reasonable ( $p_0 = 2 \times 10^6$  psi); and the stress-strain behavior described by Equation 18, the detrimental influence of the energy of deformation amounts to less than 7 percent of the energy contributed by the internal gas pressure *up to the instant of fracture*. In reality, the gases may continue to effectively accelerate the fragments even after fracture has occurred, making the values given in Table I for the energy contributed by the internal pressure valid beyond the point of fracture. Thus, the energy of deformation would negate an even smaller percentage than the previously cited energy derived from the gas pressure. Furthermore, a 7 percent change in the energy available produces just slightly more than 2.5 percent change in the fragment velocities. Such a small difference could easily go undetected or could be attributed to other variables in an actual fragmentation test.

The fragment velocity is plotted in Figure 2 as a function of radius, strain, or time (all are related) for a charge:mass ratio equal to one (corresponding to  $R_0/h_0$  equal to about 10) and an initial pressure of  $2 \times 10^6$  psi. The ultimate velocity agrees favorably with that calculated from Gurney's formula, where  $E = 55.7 \times 10^8$  inch-pounds for Composition B. Better agreement could be obtained by suitable adjustments in  $p_0$  and/or  $\gamma$ , but such manipulations are probably not meaningful in view of the approximations and assumptions already employed.

The conclusion to be drawn is that the resistance of the casing to plastic flow causes only minor attenuations in the fragment velocities. The energy attenuation is inversely proportional to the ratio of the shell radius to wall thickness, and amounts to a reduction of about 2.5 percent in the fragment velocities when the value of this ratio is as low as three.

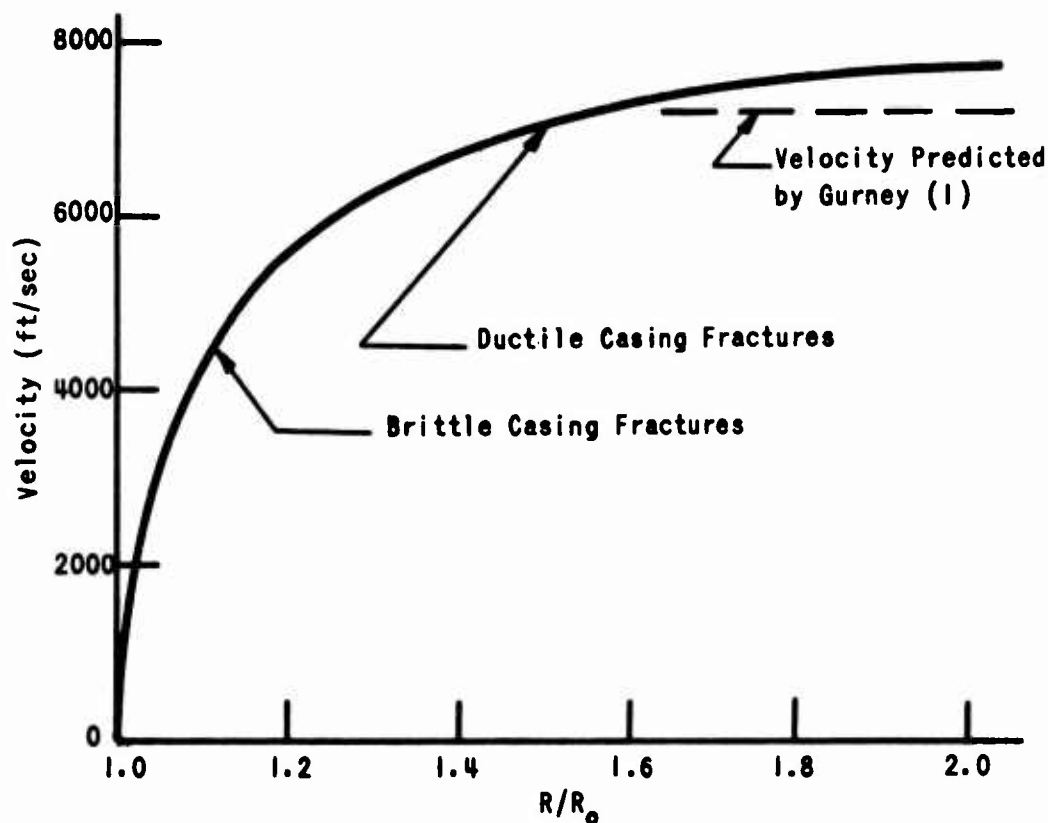


Figure 2. VELOCITY ACQUIRED BY SHELL CASING DURING ITS EXPANSION ( $C/M = 1$ ;  $p_0 = 2 \times 10^6$  psi)

It is interesting to note the difference in fragment velocities at the time of fracture for ductile and brittle casings. The ductile casing is already quite close to its ultimate velocity when fracture occurs, whereas the fragments from the brittle casing must increase their velocities by nearly 75 percent in order to achieve the same velocity. This disparity could be overcome if the explosive gases were to continue to accelerate the fragments after fracture in spite of a tendency for the gases to escape through the spaces between the fragments. The requisite forces could be derived both from a normal component due to the retained internal pressure and from a shear component resulting from the drag forces of the escaping gas. Gurney<sup>4</sup> has made some quantitative calculations which support this point of view.

<sup>4</sup>GURNEY, R. W. U. S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Report No. 635.

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